Tabulated observations of the pH tolerance of marine and estuarine biota

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TABULATED OBSERVATIONS OF

THE pH TOLERANCE OF MARINE AND ESTUARINE BIOTA

by

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Abstract

Compared to the situation in fresh waters, pH in the marine environment is well-buffered and relatively stable between 7.5 and 8.4 pH units. Nevertheless, pH can be altered outside this range by natural (e.g., photosynthesis) or anthropogenic (e.g., industrial) processes. The Canadian Water Quality Guideline for the Protection of Aquatic Life recommends that the pH of marine and estuarine waters be maintained between 7.0 and 8.7 pH units. This recommendation was based on a guideline developed by British Columbia in 1991. The present document provides an updated summary of published observations of pH tolerance of organisms in marine and estuarine habitats, including numerous studies published after 1991. This tabulation of the literature confirms that most pH-related impacts on survival, growth, photosynthesis, feeding and immune response occur at pH levels outside the recommended range. Some taxa, however, are notable for their tolerance of pH conditions well outside this range. Among the taxa tolerant of extremely high pH levels (>10-11 pH units), and potentially contributing to or even causing elevated pH through their photosynthetic activity, are several macroalgae commonly associated with "nuisance" blooms, including the green algae *Ulva lactuca* and *Enteromorpha* sp. A separate table was produced for the effects of acetic acid on biota as mortality from acetic acid exposure appears greater than that from other acids at the same pH, possibly because of the toxic effects of the acetate ion.

Résumé

Comparativement à la situation en eau douce, le pH en mer est bien tamponné et reste relativement stable, en se maintenant entre 7,5 et 8,4. Cependant, des processus naturels (p. ex., la photosynthèse) ou anthropiques (par. ex., des activités industrielles) peuvent faire baisser ou monter le pH en dehors de cette fourchette. Les Recommandations pour la qualité de l'eau en vue de la protection de la vie aquatique préconisent un maintien du pH des eaux marines et d'estuaire à une fourchette de 7 à 8,7. Ces recommandations sont fondées sur des lignes directrices élaborées par la Colombie-Britannique en 1991. Le document constitue une compilation d'observations publiées sur la tolérance d'organismes vivant dans des habitats marins et estuariens aux variations du pH, y compris de nombreuses études publiées après 1991. Cette compilation d'articles confirme que la plupart des impacts relatifs au pH sur la survie, la croissance, la photosynthèse, l'alimentation et la réaction immunitaire se manifestent à des niveaux de pH se situant à l'extérieur de la fourchette recommandée. Cependant, certains taxons se distinguent par leur tolérance à des conditions de pH qui se situent bien en dehors de cette fourchette. Parmi les taxons qui sont tolérants à des niveaux extrêmement élevés de pH (> 10 ou 11) et qui, en raison de leur activité photosynthétique, pourraient avoir un rôle dans la hausse du pH voire même en être la cause, se trouvent plusieurs macroalgues communément associées à la prolifération nuisible d'algues, y compris des algues vertes comme l'*Ulva lactuca* et l'*Enteromorpha*. Un tableau distinct, qui présente les effets de l'acide acétique sur le biote, a été créé, puisque la mortalité attribuable à une exposition à l'acide acétique est plus grande que la mortalité attribuable à d'autres acides possédant le même pH, probablement en raison des effets toxiques de l'ion acétate qu'il contient.

Introduction

While the role of hydrogen ion concentration has been extensively studied in Canada in the context of acidification of lakes and streams (e.g., NRCC 1981), pH has generally not been considered an important determinant of pelagic processes in marine environments (Hansen 2002). In comparison to the sensitivity of some fresh waters to altered hydrogen loading, the pH of sea water is relatively stable. A pH value between 7.5 and 8.4 is typical of full salinity seawater (Sverdrup et al. 1942), although photosynthesis can increase pH to 9 and rarely even to 10 in estuaries (Hansen 2002). Nevertheless, the pH of the ocean can be affected by anthropogenic factors operating on scales ranging from global to local. Oceanic absorption of CO_2 from fossil fuels is expected to result in larger pH changes over the next several centuries than any inferred from the geological record of the past 300 million years (Caldeira and Wickett 2003). Relative to preindustrial times, the oceans had acidified by 0.1 pH units by the year 2000, and geochemical models forecast a further decrease of nearly 0.8 pH units by the year 2300 (Pelejero et al. 2005). On the local scale, the pH of water bodies can be affected by additions of acidic or alkaline materials from industrial processes or other human activities. The compilation of literature summarized in the present document was motivated by a need to examine the effects on the surrounding environment of potentially pH-altering treatments (acetic acid and hydrated lime) used in the bivalve aquaculture industry to control fouling (Locke et al., in review).

An interim guideline for pH in Canadian marine and estuarine waters (published in CCME 1999, after CCME 1996) is as follows:

"The pH of marine and estuarine waters should fall within the range of 7.0-8.7 units unless it can be demonstrated that such a pH is a result of natural processes. Within this range, pH should not vary by more than 0.2 pH units from the natural pH expected at that time. Where pH is naturally outside that range, human activities should not cause pH to change by more than 0.2 pH units from the natural pH expected at that time, and any change should tend towards the recommended range (CCME 1996)."

The interim Canadian guideline was based largely on the guideline published for British Columbia in 1991 (CCME 1999). The objective of the present document is to provide, in tabular form, an updated summary of published pH observations on marine and estuarine organisms.

Methods

The scientific literature was searched for information on the pH tolerances of marine and estuarine biota. Relevant data were found in 49 papers. The data were reported here as given; no attempt was made to standardize the endpoints. A few authors conducted bioassays and reported the results as toxicological standard measurements such as "EC50" (pH at which 50% of organisms were affected), but these were the

exceptions. Unless otherwise specified, the given endpoint represents the level above or below which an observational study determined 100% mortality (or cessation of reproduction, feeding, etc.) occurred. Thus, a table entry for "Tolerance of acidic pH" indicating an endpoint of "Photosynthesis" and critical pH "7.0" would indicate that the organism was unable to photosynthesize at pH levels below 7.0. Likewise, an entry under "Tolerance of alkaline pH" citing a critical pH of "8.5" for endpoint "Mortality" would indicate no survival at pH > 8.5.

The results were tabulated by taxonomic/functional groups; heterotrophic microorganisms, Plantae (algae) and autotrophic microorganisms, Plantae (vascular macrophytes), Mollusca (Bivalvia), Arthropoda, other invertebrates, Ascidiacea, and Osteichthyes. Classification followed the Catalogue of Life: 2008 Taxonomic Checklist (www.catalogueoflife.org, accessed 23 July 2008). Within each taxonomic/functional group, pH tolerances were listed from lowest to highest pH.

A separate table was produced for tolerances of organisms to acetic acid. This pH-altering chemical has been of special interest in recent years for its potential to control abundances of Ascidiacea on aquaculture structures. Acetic acid appears to be more biocidal than other acids adjusted to the same pH (Forrest et al. 2007; Locke et al. in review), possibly because at pH <6.5, acetic acid acts to uncouple cellular communication (Germain and Anctil 1996).

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Table 1. pH tolerance of marine heterotrophic microorganisms.

(a) Tolerance of acidic pH

Taxon (Phylum) or functional group	**Endpoint**	**Critical pH**	**Source**
Methane bacteria	50% reduced growth	5.0	Hutton and Zobell 1949
Aerobic heterotrophs	50% reduced growth	6.5	Zobell 1941

(b) Tolerance of alkaline pH

Taxon (Phylum) or functional group	**Endpoint**	**Critical pH**	**Source**
Favella ehrenbergii, *Rimostrombidium caudatum*, *R. veniliae* (Ciliophora)	Reduced growth	8.8	Pederson and Hansen 2003
Favella ehrenbergii, *Rimostrombidium caudatum*, *R. veniliae* (Ciliophora)	Growth	9.0	Pederson and Hansen 2003
Favella ehrenbergii, *Rimostrombidium caudatum*, *R. veniliae* (Ciliophora)	24 h mortality	9.3	Pederson and Hansen 2003
Balanion comatum (Ciliophora)	Reduced growth	9.5	Pedersen and Hansen 2003

Table 2. pH tolerance of marine algae and photosynthetic microorganisms.

(a) Tolerance of acidic pH

Taxon (Phylum, Class)	**Endpoint**	**Critical pH**	**Source**
Ulva lactuca (Chlorophyta, Ulvophyceae)	Mortality	6.0-6.5	Hampson 1967
Prorocentrum micans, *Peridinium* sp. (Dinophyta, Dinophyceae)	Growth	6.0-7.0	Barker 1935
Halimeda tuna (Chlorophyta, Bryopsidophyceae)	Calcification	6.5	Borowitzka and Larkum 1976
Palmaria longata (Rhodophyta, Florideophyceae)	Photosynthesis	6.5	Robbins 1977
Coccolithus (Emiliana) huxleyi (Haptophyta, Prymnesiophyceae)	Photosynthesis	6.7	Paasche 1976
Ectocarpus sp. (Ochrophyta, Phaeophyceae)	Growth	7.0	Boalch 1961
Bossiella orbigniana (Rhodophyta, Florideophyceae)	Calcification	7.0	Smith and Roth 1979
Nitzchia sp., *Navicula* sp. (Bacillariophyta)	Growth	7.0	Bachrach and Luccicardi 1932
Porphyra sp. (Rhodophyta, Bangiophyceae), *Petalonia* sp. (Ochrophyta, Phaeophyceae), *Ulva* sp. (Chlorophyta, Ulvophyceae)	Photosynthesis	7.0	Ogata 1966
Cricosphaera longate (Haplophyta, Prymnesiophyceae)	Growth	7.4	Swift and Taylor 1966

Table 2. Continued.

(b) Tolerance of alkaline pH

Taxon (Phylum) or functional group	**Endpoint**	**Critical pH**	**Source**
Ceratium tripos (Dinophyta, Dinophyceae)	20% reduction in growth	8.24	Schmidt and Hansen 2001
Ceratium furca (Dinophyta, Dinophyceae)	20% reduction in growth	8.29	Schmidt and Hansen 2001
Ceratium lineatum (Dinophyta, Dinophyceae)	20% reduction in growth	8.30	Schmidt and Hansen 2001
Ceratium tripos (Dinophyta, Dinophyceae)	Growth	8.30	Schmidt and Hansen 2001
Dictyocha speculum (Ochrophyta, Chrysophyceae)	20% reduction in growth	8.30	Schmidt and Hansen 2001
Ceratium furca (Dinophyta, Dinophyceae)	Growth	8.40	Schmidt and Hansen 2001
Skeletonema costatum (Bacillariophyta)	20% reduction in growth	8.49	Schmidt and Hansen 2001
Cylindrotheca closterium (Bacillariophyta)	Growth	8.5	Humphrey 1975
Heterosigma akashiwo (Ochrophyta, Raphidophyceae)	20% reduction in growth	8.52	Schmidt and Hansen 2001
Pyramimonas propulsa (Prasinophyta, Prasinophyceae)	20% reduction in growth	8.55	Schmidt and Hansen 2001
Alexandrium ostenfeldii (Dinophyta, Dinophyceae)	20% reduction in growth	8.66	Schmidt and Hansen 2001

Table 2. Continued.

Taxon (Phylum) or functional group	Endpoint	Critical pH	Source
Alexandrium tamarense (Dinophyta, Dinophyceae)	20% reduction in growth	8.66	Schmidt and Hansen 2001
Dunaliella tertiolecta (Prasinophyta, Prasinophyceae)	Growth	8.69	Elzenga and Prins 2000
Chrysochromulina polylepis (Haptophyta, Prymnesiophyceae)	20% reduction in growth	8.70	Schmidt and Hansen 2001
Gymnodinium mikimotoi (Dinophyta, Dinophyceae)	20% reduction in growth	8.72	Schmidt and Hansen 2001
Rhodomonas marina (Cryptophyta, Cryptophyceae)	20% reduction in growth	8.74	Schmidt and Hansen 2001
Prorocentrum micans (Dinophyta, Dinophyceae)	20% reduction in growth	8.75	Schmidt and Hansen 2001
Ceratium lineatum (Dinophyta, Dinophyceae)	Growth	8.79	Schmidt and Hansen 2001
Heterocapsa triquetra (Dinophyta, Dinophyceae)	20% reduction in growth	8.8-8.9	Schmidt and Hansen 2001
Emiliana huxleyi (weak coccoliths) (Prymnesiophyta, Prymnesiophyceae)	Growth	8.80	Elzenga and Prins 2000
Pyramimonas propulsa (Prasinophyta, Prasinophyceae)	Growth	8.80	Schmidt and Hansen 2001
Dictyocha speculum (Ochrophyta, Chrysophyceae)	Growth	8.81	Schmidt and Hansen 2001

Table 2. Continued.

Taxon (Phylum) or functional group	Endpoint	Critical pH	Source
Alexandrium tamarense (Dinophyta, Dinophyceae)	Growth	8.85	Schmidt and Hansen 2001
Alexandrium ostenfeldii (Dinophyta, Dinophyceae)	Growth	8.90	Schmidt and Hansen 2001
Thalassiosira punctigera (Bacillariophyta)	Growth	8.90	Elzenga and Prins 2000
Biddulphia aurita (Bacillariophyta)	Growth	9	Humphrey 1975
Chaetoceros didymus (Bacillariophyta)	Growth	9	Humphrey 1975
Skeletonema costatum (Diatomaceae)	Growth	9.0	Rajaretnam et al. 1987
Eutreptiella gymnastica (Euglenozoa, Euglenida)	20% reduction in growth	9.00	Schmidt and Hansen 2001
Gymnodinium mikimotoi (Dinophyta, Dinophyceae)	Growth	9.00	Schmidt and Hansen 2001
Gymnodinium splendens (Dinophyta, Dinophyceae)	Growth	9	Humphrey 1975
Monochrysis lutheri (Ochrophyta, Synurophyceae)	Growth	9	Humphrey 1975
Phaeocystis globosa (Haptophyta, Prymnesiophyceae)	Growth	9.14	Elzenga and Prins 2000
Heterosigma akashiwo (Ochrophyta, Raphidophyceae)	Growth	9.15	Schmidt and Hansen 2001

Table 2. Continued.

Taxon (Phylum) or functional group	Endpoint	Critical pH	Source
Chrysochromulina polylepis (Haptophyta, Prymnesiophyceae)	Growth	9.20	Schmidt and Hansen 2001
Chrysochromulina simplex (Haptophyta, Prymnesiophyceae)	20% reduction in growth	9.20	Schmidt and Hansen 2001
Gymnodinium dominans (Dinophyta, Dinophyceae)	Reduced growth	9.2	Pedersen and Hansen 2003
Prorocentrum minimum (Dinophyta, Dinophyceae)	20% reduction in growth	9.20	Schmidt and Hansen 2001
Skeletonema costatum (Bacillariophyceae)	Growth	9.21	Schmidt and Hansen 2001
Eutreptiella gymnastica (Euglenozoa, Euglenida)	Growth	9.22	Schmidt and Hansen 2001
Chrysochromulina simplex (Haptophyta, Prymnesiophyceae)	Growth	9.25	Schmidt and Hansen 2001
Emiliana huxleyi (heavy coccoliths) (Haptophyta, Prymnesiophyceae)	Growth	9.29	Elzenga and Prins 2000
Chroomonas sp. (Cryptophyta, Cryptophyceae)	Growth	9.3	Humphrey 1975
Gymnodinium dominans (Dinophyta, Dinophyceae)	Growth	9.4	Humphrey 1975
Synechococcus sp. (Cyanobacteria)	Growth	9.40	Elzenga and Prins 2000
Heterocapsa triquetra (Dinophyta, Dinophyceae)	Growth	9.43	Schmidt and Hansen 2001

Table 2. Continued.

Taxon (Phylum) or functional group	Endpoint	Critical pH	Source
Dunaliella tertiolecta (Prasinophyta, Prasinophyceae)	Growth	9.5	Humphrey 1975
Nitzschia closterium (Bacillariophyta)	Growth	9.5	Humphrey 1975
Thalassiosira fluviatilis (Diatomaceae)	Mortality	9.5	Rajaretnam et al. 1987
Ceramium rubrum, *Polysiphonia fucum* (Rhodophyta, Florideophyceae), *Chaetomorpha linum* (Chlorophyta, Ulvophyceae)	Photosynthesis	9.5-9.7	Sand-Jensen and Gordon 1984
Prorocentrum minimum (Dinophyta, Dinophyceae)	Growth	9.62	Schmidt and Hansen 2001
Thalassiosira pseudonana (Bacillariophyta)	Growth	9.77	Elzenga and Prins 2000
Prorocentrum micans (Dinophyta, Dinophyceae)	Growth	9.92	Schmidt and Hansen 2001
Rhodomonas marina (Cryptophyta, Cryptophyceae)	Growth	9.93	Schmidt and Hansen 2001
Gymnodinium dominans (Dinophyta, Dinophyceae)	5-day mortality	10	Pedersen and Hansen 2003
Phaeodactylum tricornutum (Bacillariophyta)	Growth	10	Humphrey 1975
Amphidinium carterae (Dinophyta, Dinophyceae)	Growth	10	Humphrey 1975
Nannochloropsis sp. (Ochrophyta, Eustygmataphyceae)	Growth	10.08	Elzenga and Prins 2000

Table 2. Continued.

Taxon (Phylum) or functional group	**Endpoint**	**Critical pH**	**Source**
Phaeodactylum tricornutum (Bacillariophyta)	Growth	10.3	Goldmann et al. 1982
Phaeodactylum tricornutum (Bacillariophyta)	Growth	10.4	Nimer et al. 1997
Fucus vesiculosus (Ochrophyta, Phaeophyceae)	Photosynthesis	10.4	Sand-Jensen and Gordon 1984
Ulva lactuca, *Enteromorpha* sp. (Chlorophyta, Ulvaceae)	Photosynthesis	>10.4 (photosynthesis continued at 10.4, the highest pH tested)	Sand-Jensen and Gordon 1984
Ulva lactuca (Chlorophyta, Ulvophyceae)	Mortality	>11.6 (this pH is reached in floating mats in Denmark)	Sand-Jensen and Gordon 1984

Table 3. pH tolerance of marine macrophytes.

(a) Tolerance of acidic pH

Taxon	**Endpoint**	**Critical pH**	**Source**
Zostera muelleri	Reduced photosynthesis	7.8	Millhouse and Strother 1986

(b) Tolerance of alkaline pH

Taxon (Phylum) or functional group	**Endpoint**	**Critical pH**	**Source**
Ruppia longata, Zostera marina	Photosynthesis	10-10.2	Sand-Jensen and Gordon 1984

Table 4. pH tolerance of marine Bivalvia (Mollusca).

(a) Tolerance of acidic pH

Taxon	Endpoint	Critical pH	Source
Crassostrea gigas (~1 cm)	Mortality	6.0	Bamber 1990
Venerupis longata	Mortality	6.1-6.4	Bamber 1987
Crassostrea virginica larva	Mortality	6.25	Calabrese and Davis 1966
Mercenaria mercenaria larva	Mortality	6.25	Calabrese and Davis 1966
Mulina lateralis larva	Mortality	6.50	Calabrese 1970
Ostrea virginica	Pumping frequency and opening time	6.5	Loosanoff and Tommers 1947
Crassostrea gigas	Gaping valves	6.6	Bamber 1990
Mytilis edulis (≤5 cm)	Mortality	6.6	Bamber 1990
Mytilus edulis	Gaping valves	6.6	Bamber 1990
Ostrea edulis (~1 cm)	Mortality	6.6	Bamber 1990
Ostrea edulis	Gaping valves	6.6	Bamber 1990
Crassostrea virginica	Normal growth	6.75	Calabrese and Davis 1966
Mercenaria mercenaria	Normal growth	6.75	Calabrese and Davis 1966
Ostrea edulis (~4 cm)	Mortality	6.9	Bamber 1990
Crassostrea gigas	Weight	7.0	Bamber 1990
Mercenaria mercenaria	Embryonic development	7.0	Calabrese and Davis 1966
Mulina lateralis	Larval growth	7.0	Calabrese 1970
Mytilus edulis	Increased heart beat	7.0	Schlieper 1955 cited in Knutzen 1981
Ostrea edulis	Weight	7.0	Bamber 1990
Ostrea edulis	Growth in length	7.0	Bamber 1990
Ostrea edulis	Normal larval development	7.0	Gaarder 1932
Venerupis elongata	Feeding	7.0	Bamber 1987
Venerupis elongata	Shell growth	7.0	Bamber 1987
Venerupis elongata	Flesh weight	7.0	Bamber 1987
Crassostrea gigas	Feeding rate	7.2	Bamber 1990
Mytilus edulis	Feeding rate	7.2	Bamber 1990
Ostrea edulis	Feeding rate	7.2	Bamber 1990

Table 4. Continued.

Taxon	Endpoint	Critical pH	Source
Mulina lateralis	Normal embryonic development	7.25	Calabrese 1970
Pintada fucata	Adult mortality	7.48	Kuwatani and Nishii 1969
Venerupis elongata	Shell dissolution	7.5	Bamber 1987
Mytilus edulis	Gamete respiration	7.6	Akberali et al. 1985
Pintada fucata	Shell dissolution	7.66	Kawatani and Nishii 1969
Mytilus spp.	Normal larval development	7.75	SFEI 1997

(b) Tolerance of alkaline pH

Taxon (Phylum) or functional group	Endpoint	Critical pH	Source
Mulina lateralis	Normal embryonic development	8.25	Calabrese 1970
Mulina lateralis larva	Growth	8.5	Calabrese 1970
Crassostrea virginica larva	Mortality	8.75	Calabrese and Davis 1966
Crassostrea virginica	Normal growth	8.75	Calabrese and Davis 1966
Mercenaria mercenaria larva	Mortality	8.75	Calabrese and Davis 1966
Mulina lateralis larva	Mortality	8.75	Calabrese 1970
Mytilus spp.	Normal larval development	8.75	SFEI 1997
Crassostrea virginica	Embryonic development	9.0	Calabrese and Davis 1966
Mercenaria mercenaria	Embryonic development	9.0	Calabrese and Davis 1966

Table 5. pH tolerance of marine Arthropoda.

(a) Tolerance of acidic pH

Taxon (Class, Order)	**Endpoint**	**Critical pH**	**Source**
Themisto japonica (Malacostraca, Euphausiacea)	24-h LC50	4.74	Yamada and Ikeda 1999
Eucalanus bungii bungii (Maxillopoda, Calanoida)	24-h LC50	4.79	Yamada and Ikeda 1999
Panulirus homarus (Malacostraca, Decapoda)	Impaired immune system	Between 5.0 and 8.0	Verghese et al. 2007
Metridia pacifica (Maxillopoda, Calanoida)	24-h LC50	5.07	Yamada and Ikeda 1999
Euphausia pacifica nauplii (Malacostraca, Euphausiacea)	24-h LC50	5.22	Yamada and Ikeda 1999
Neocalanus cristatus (Maxillopoda, Calanoida)	24-h LC50	5.39	Yamada and Ikeda 1999
Conchoecia sp. (Ostracoda, Halocyprida)	24-h LC50	5.40	Yamada and Ikeda 1999
Temora longicornis (Maxillopoda, Calanoida)	Mortality	5.5	Grice et al. 1973
Eucalanus bungii bungii (Maxillopoda, Calanoida)	168-h LC50	5.53	Yamada and Ikeda 1999
Pseudocalanus minutus (Maxillopoda, Calanoida)	24-h LC50	5.57	Yamada and Ikeda 1999
Metridia pacifica (Maxillopoda, Calanoida)	72-h LC50	5.68	Yamada and Ikeda 1999
Calanus pacificus (Maxillopoda, Calanoida)	24-h LC50	5.83	Yamada and Ikeda 1999

Table 5. Continued.

Taxon	Endpoint	Critical pH	Source
Euphausia pacifica juveniles (Malacostraca, Euphausiacea)	24-h LC50	5.93	Yamada and Ikeda 1999
Armases spp. (Malacostraca, Decapoda)	Normal development to 2nd larval stage	6	Diesel et al. 2000
Pseudocalanus minutus (Maxillopoda, Calanoida)	144-h LC50	6.02	Yamada and Ikeda 1999
Euphausia pacifica nauplii (Malacostraca, Euphausiacea)	120-h LC50	6.10	Yamada and Ikeda 1999
Calanus pacificus (Maxillopoda, Calanoida)	120-h LC50	6.14	Yamada and Ikeda 1999
Neocalanus cristatus (Maxillopoda, Calanoida)	24-h LC50	6.16	Yamada and Ikeda 1999
Paraeuchaeta elongata (Maxillopoda, Calanoida)	24-h LC50	6.23	Yamada and Ikeda 1999
Conchoecia sp. (Ostracoda, Halocyprida)	120-h LC50	6.44	Yamada and Ikeda 1999
Acartia tonsa (Maxillopoda, Calanoida)	Mortality	6.7	Rose et al. 1977
Themisto japonica (Malacostraca, Euphausiacea)	168-h LC50	6.70	Yamada and Ikeda 1999
Paraeuchaeta elongata (Maxillopoda, Calanoida)	144-h LC50	6.83	Yamada and Ikeda 1999
Euphausia pacifica juveniles (Malacostraca, Euphausiacea)	168-h LC50	6.84	Yamada and Ikeda 1999

Table 5. Continued.

Taxon	Endpoint	Critical pH	Source
Penaeus monodon (Malacostraca, Decapoda)	Loss of physiological control over mineralization	7.4	Wickins 1984

(b) Tolerance of alkaline pH

Taxon (Phylum) or functional group	Endpoint	Critical pH	Source
Panulirus homarus (Malacostraca, Decapoda)	Impaired immune system	Between 8.0 and 9.5	Verghese et al. 2007
Armases spp. (Malacostraca, Decapoda)	Normal development to 2nd larval stage	8.5	Diesel et al. 2000
Sesarma curacaoense (Malacostraca, Decapoda)	Normal development to 2nd larval stage	8.5	Diesel et al. 2000

Table 6. pH tolerances of marine invertebrates other than Mollusca (Bivalvia) and Arthropoda.

(a) Tolerance of acidic pH

Taxon (Phylum)	**Endpoint**	**Critical pH**	**Source**
Procephalothrix simulus (Nemertea)	Mortality	5	Zhao and Sun 2006
Sagitta elegans (Chaetognatha)	24-h LC50	5.91	Yamada and Ikeda 1999
Sepiella inermis (=S. maindroni) (Cephalopoda)	Larval mortality	6	Yin et al. 2005
Sagitta elegans (Chaetognatha)	72-h LC50	6.73	Yamada and Ikeda 1999

(b) Tolerance of alkaline pH

Taxon (Phylum) or functional group	**Endpoint**	**Critical pH**	**Source**
Procephalothrix simulus (Nemertea)	Mortality	9.20	Zhao and Sun 2006
Sepiella inermis (=S. maindroni) (Cephalopoda)	Larval mortality	9.5	Yin et al. 2005

Table 7. pH tolerance of marine chordates (Ascidea).

(a) Tolerance of acidic pH

Taxon	Endpoint	Critical pH	Source
Ciona intestinalis	Normal larval development	6.9	Bellas et al. 2003

(b) Tolerance of alkaline pH

Taxon (Phylum) or functional group	Endpoint	Critical pH	Source
Ciona intestinalis	Normal larval development	9.0	Bellas et al. 2003

Table 8. pH tolerance of marine chordates (Osteichthyes).

(a) Tolerance of acidic pH

Taxon	Endpoint	Critical pH	Source
Heteromycteris capensis	24 h LC50	4.48	Brownell 1980
Sparus aurata	24 h LC50	4.82-5.55	Parra and Yūfera 2002
Solea senegalensis	24 h LC50	4.88-5.76	Parra and Yūfera 2002
Heteromycteris capensis	24 h LC10	4.51	Brownell 1980
Gaidropsarus capensis	24 h LC50	4.74	Brownell 1980
Gaidropsarus capensis	24 h LC10	4.99	Brownell 1980
Diplodus sargus	24 h LC50	5.06	Brownell 1980
Diplodus sargus	24 h LC10	5.17	Brownell 1980
Diplodus sargus	24 h first-feeding EC50	5.20	Brownell 1980
Gaidropsarus capensis	24 h first-feeding EC50	5.22	Brownell 1980
Diplodus sargus	24 h first-feeding EC10	5.69	Brownell 1980
Heteromycteris capensis	24 h first-feeding EC50	5.90	Brownell 1980
Gaidropsarus capensis	24 h first-feeding EC10	5.91	Brownell 1980
Atherina boyeri	Avoidance	6.5	Davies 1991

(b) Tolerance of alkaline pH

Taxon	Endpoint	Critical pH	Source
Gaidropsarus capensis	24 h first-feeding EC10	8.39	Brownell 1980
Heteromycteris capensis	24 h first-feeding EC10	8.50	Brownell 1980
Diplodus sargus	24 h first-feeding EC10	8.52	Brownell 1980
Sparus aurata	24 h LC50	8.66-9.26	Parra and Yūfera 2002
Gaidropsarus capensis	24 h first-feeding EC50	8.67	Brownell 1980
Heteromycteris capensis	24 h first-feeding EC50	8.78	Brownell 1980

Table 8. Continued.

Taxon	Endpoint	Critical pH	Source
Diplodus sargus	24 h LC10	8.89	Brownell 1980
Heteromycteris capensis	24 h LC10	8.92	Brownell 1980
Gaidropsarus capensis	24 h LC10	8.99	Brownell 1980
Diplodus sargus	24 h LC50	9.04	Brownell 1980
Diplodus sargus	24 h LC50	8.82	Brownell 1980
Solea senegalensis	24 h LC50	8.94-9.57	Parra and Yūfera 2002
Heteromycteris capensis	24 h LC50	9.21	Brownell 1980
Gaidropsarus capensis	24 h LC50	9.24	Brownell 1980

Table 9. Effects of exposure to acetic acid on marine organisms.

(a) Algae

Taxon	Endpoint	% Acetic acid	Immersion time (min)	Source
Cladophora sp. (Chlorophyta, Ulvophyceae)	Mortality	2%	3 min	Forrest et al. 2007
Cladophora sp. (Chlorophyta, Ulvophyceae)	Mortality	4%	1 min	Forrest et al. 2007
Green alga (Chlorophyta)	Mortality	5%	15 sec	Sharp et al. 2006
Undaria pinnatifida (Ochrophyta, Phaeophyceae) gametophyte and plantlet	Mortality	<1%	1 min	Forrest et al. 2007
Undaria pinnatifida (Ochrophyta, Phaeophyceae) sporophyte	Mortality	4%	1 min	Forrest et al. 2007

(b) Bivalvia (Mollusca)

Taxon	Endpoint	% Acetic acid	Immersion time (min)	Source
Mytilus edulis spat	>60% unattached or gaping open 24 h after exposure	5%	20 sec	Sharp et al. 2006
Mytilus edulis spat	Death or lack of growth	5%	Repeated 15 sec immersion	Sharp et al. 2006
Mytilus edulis	74% reduction in sock weight after 7 mo	5%	30 sec	LeBlanc et al. 2007
Mytilus edulis	86% reduction in sock weight after 7 mo	5%	2 min	LeBlanc et al. 2007

Table 9. Continued.

Taxon	Endpoint	% Acetic acid	Immersion time (min)	Source
Perna canaculus	Attachment >95% after 1 mo	4%	2 min, rinsed	Forrest et al. 2007
Perna canaculus	Attachment <57% after 1 mo	4%	2 min, not rinsed	Forrest et al. 2007
Perna canaculus	Attachment <26% after 1 mo	8%	2 min, not rinsed	Forrest et al. 2007

(c) Invertebrates other than Bivalvia

Taxon	Endpoint	% Acetic acid	Immersion time (min)	Source
Bugula neritina (Bryozoa)	Mortality	4%	1 min	Forrest et al. 2007
Watersipora subtorquata (Bryozoa)	Mortality	4%	1 min	Forrest et al. 2007
Hydroides elegans (Polychaeta)	Mortality	4%	4 min, air-dried, transported 24 h	Forrest et al. 2007
Terebellidae (Polychaeta)	Mortality	2%	3 min	Forrest et al. 2007
Terebellidae (Polychaeta)	Mortality	4%	2 min	Forrest et al. 2007

(d) Ascidea

Taxon	Endpoint	% Acetic acid	Immersion time (min)	Source
Botrylloides leachi	Mortality	4%	1 min	Forrest et al. 2007
Botryllus schlosseri	Mortality	4%	1 min	Forrest et al. 2007
Ciona intestinalis	Mortality	2%	1 min, air-dried	Forrest et al. 2007
Ciona intestinalis	Mortality	4%	4 min	Forrest et al. 2007

Table 9. Continued.

Taxon	Endpoint	% Acetic acid	Immersion time (min)	Source
Cnemidocarpa bicornuata	Mortality	2%	1 min, air-dried	Forrest et al. 2007
Corella eumyota	Mortality	2%	1 min, air-dried	Forrest et al. 2007
Corella eumyota	Mortality	4%	4 min	Forrest et al. 2007
Styela clava	66% mortality after 1 wk	1%	5 min	Coutts and Forrest 2005
Styela clava	100% mortality after 1 wk	1%	10 min	Coutts and Forrest 2005
Styela clava	100% mortality after 1 wk	2%	5 min	Coutts and Forrest 2005
Styela clava	100% mortality after 1 wk	4% and 5%	1 min	Coutts and Forrest 2005